LUMOS: Designing an Interactive Companion Robot to Enhance Critical Reading and Thinking in Academic Contexts

Yaxuan Mao[1*†], Yanheng Li[2*], Yuzhuo Jia[3], Fanhong Li[4], Zi Yin[4], Shurui Zheng[4]

***Abstract*— Critical reading requires understanding textual content, organizing and articulating reasoning about arguments and evidence. While prior work has explored screen-based tools to support reading, less is known about how embodied systems may shape higher-order cognitive processes during academic reading. In this paper, we investigate how a non-humanoid desktop robot can support critical academic reading. To explore this question, we developed *LUMOS*, a robotic reading companion that provides ambient cues for attention regulation and dialogic prompts for reflection. Through a within-subject study comparing robot-assisted and independent reading, we found that robot-mediated scaffolding is associated with improvements in comprehension accuracy and the quality of critical writing. Notably, while participants did not generate more viewpoints, their arguments became more structured and coherent. These findings suggest that robotic companions act as interactional scaffolds that shape how readers structure and externalize their reasoning, rather than increasing the number of ideas they produce. Furthermore, qualitative findings suggest that such benefits can emerge from subtle, non-intrusive interaction, without requiring strong social presence.**

I. INTRODUCTION

Academic reading requires moving beyond basic comprehension to critically evaluate arguments, evidence, and underlying assumptions [1]. This involves connecting claims with supporting evidence and situating ideas within broader scholarly conversations. However, many students, especially novice researchers, struggle to sustain active engagement with complex academic materials, lacking support for tracing connections across ideas, synthesizing arguments, and distilling their own positions. Existing support primarily relies on instructional strategies or screen-based tools, such as annotation systems, metacognitive prompts, and digital reading interfaces [2], [3]. While these approaches facilitate comprehension and reflection, they often overlook the role of physical materials and embodied interactions in supporting higher-order cognitive skills including critical thinking [4].

Recent work in human–robot interaction suggests that social robots can support learning and cognitive tasks [5]. Through embodied presence and socially grounded interaction, robots can provide prompts and feedback that encourage engagement and reflection. Prior studies have explored robots as reading companions, assisting children with oral reading practice or motivation [6], [7]. However, limited research has examined how robotic systems support higher-level academic reading processes such as attention regulation, argument analysis, and reflective critique. Unlike highly expressive humanoid robots designed to attract and sustain user attention [8], ambient robotic systems [9] can remain at the periphery of users' awareness, providing subtle cues such as light, movement, or posture to regulate attention and prompt reflection [10]. Despite this potential, their integration into academic reading remains underexplored.

In this work, we investigate how an embodied robotic companion can support reflective academic reading. To explore this question, we developed LUMOS (**L**earning and **U**nderstanding through a **M**entoring **O**riented **S**ystem)[1], a non-humanoid desktop robot that provides ambient cues for attention regulation and dialogic prompts for reflection during paper-based reading. Through a within-subject study comparing robot-assisted and independent reading, we examine how robotic companions may shape readers' organization, articulation, and reflection during academic reading. We addressed the following research questions:

RQ1: How can an ambient robot companion support reading and reflective engagement during academic reading?

RQ2: How does interaction with such a robot influence students' critical reading behaviors and reading experience?

This paper makes three main contributions: (1) the design and implementation of LUMOS, an ambient robotic companion for academic reading; (2) empirical evidence that robot-assisted reading improves comprehension and the quality of critical writing; and (3) theoretical insights showing that robotic support acts as a interactional scaffold by enhancing the structure and coherence of reasoning without increasing the number of viewpoints, and that these benefits do not rely on strong social presence, highlighting the value of subtle, non-intrusive interaction for cognitively demanding tasks.

II. RELATED WORK

A. Academic Reading and Critical Thinking

Academic reading in higher education requires readers to go beyond information extraction and build an argument-level understanding by connecting claims with evidence [11]. Beyond comprehension, critical reading further involves evaluating claim validity, potential bias, and evidence strength, supported by metacognitive monitoring, such as noticing confusion and regulating attention [1].

*These authors contributed equally to this work.

†Coresponding author

[1]Human Centered Design & Engineering, University of Washington, Seattle, WA 98195, USA stellayx@uw.edu

[2]School of Creative Media, City University of Hong Kong, Hong Kong SAR yanhengli3-c@my.cityu.edu.hk

[3]School of Computer Science, The University of Sydney, Australia

[4]Laboratory of Brain and Intelligence, Tsinghua University, China

[1]The name also nods to the *Lumos* spell from *Harry Potter*, reflecting the system's aim to illuminate readers' thinking.

These practices are central to critical thinking and evidence based reasoning, yet many undergraduates and novice graduate students struggle to sustain analytical engagement and tend to skim or accept texts uncritically [12]. To address these challenges, existing support for academic reading is largely based on instructional and screen-based tools, such as strategy training and annotation [2], [3]. However, these approaches ignore the hybrid reality where many scholars still rely on physical affordances (e.g., spatial layout, bimanual interaction) for better sense-making performance [13]. Therefore, we identify an opportunity to augment these physical practices with subtle and activity-embedded support that integrates naturally into readers' physical workspace.

B. Social Robots as Reading and Learning Companions

Social robots have been increasingly investigated as learning companions that provide feedback, encouragement, and guided questioning, leveraging embodiment and social presence to support engagement and learning outcomes [5]. Prior work on reading with social robots has largely focused on foundational literacy and oral reading practice, reporting benefits in participation, practice quality, or affective experience when robots act as reading partners [14]. However, academic reading places greater emphasis on evaluating arguments and evidence, while prior work offers limited insight into how social robots can support these higher-order processes. This gap motivates the design of companions that remain present yet minimally intrusive while enabling structured reflection.

C. Non-humanoid Robots as Ambient Support

Beyond socially expressive learning companions, non-humanoid robots have also been explored as ambient companions that support cognitive tasks through peripheral interaction, reducing the social pressure and attentional demand often associated with humanoid robots [10]. In such systems, subtle cues such as light, movement, or posture can regulate attention and prompt re-engagement while remaining in the background of users' awareness [9], [15], [16]. These qualities give ambient non-humanoid robots great potential to integrate into the reading context, which requires the reader's focused attention. To address this gap, our work designed and examined a non-humanoid desktop robot intended to provide ambient support for attention regulation and critical reading.

III. LUMOS

We designed LUMOS, a desktop reading companion that provides ambient embodied support for academic reading.

Informed by research on learning theories and human-robot interaction, we identified the following design goals for LUMOS to foster essential abilities for academic reading:

A. Design Goals

DG1 Fostering conceptual understanding via multi-sensory experiences. Grounded in embodied cognition theories [17], the system embeds visual projection and audio cues that support meaning-making directly into the physical reading context, aiming to support conceptual understanding while maintaining focus on reading materials.

DG2 Encouraging reflective reading via dialogic revisiting. Drawing on dialogic learning theories [18], which emphasize understanding through iterative engagement, the system prompts readers to pause and re-evaluate earlier sections. This design fosters a non-linear reading process, encouraging users to articulate and reconsider their interpretations through dialogic interaction.

DG3 Externalizing thought processes via social dialog. Leveraging cognitive apprenticeship [19] and the CASA paradigm [20], the robot functions as a socially situated interlocutor. By eliciting explanation and evaluation, the system prompts readers to externalize tacit reasoning processes, transforming internal thought into explicit verbalization.

DG4 Scaffolding critical thinking via reciprocal interactions. Adapting reciprocal teaching strategies [21], the system employs an interaction structure where control alternates between the reader and the robot, supporting critical thinking behaviors (e.g., questioning, summarizing). Social signals are used to maintain turn-taking and engagement, reinforcing the reciprocal nature of the interaction [22], [23].

B. System Design

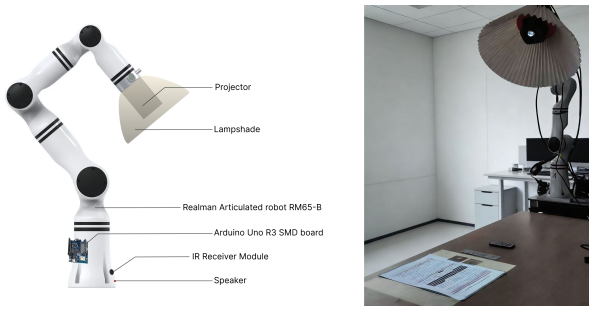


Fig. 1. Hardware configuration and physical deployment of LUMOS.

The interaction with LUMOS is organized around two modes aligned with the design goals: *Reading Mode* supports sustained attention to reading materials through ambient knowledge cues, and *Critical Mode* facilitates reflective and analytical engagement through socially grounded, dialogic interactions with the robot. Users retain full control over when and how the system intervenes, allowing the system to adapt to individual reading experiences and preferences.

a) Reading Mode: Reading Mode provides subtle visual and auditory cues. Visual projections include brief markers overlays on the paper highlighting key sentences or displaying structural cues such as simplified mind maps (DG1). In parallel, brief audio prompts introduce reflective questions that nudge readers to reconsider the material from alternative perspectives (DG2).

b) Critical Mode: Critical Mode supports reflective and analytical reading by shifting the robot's role from ambient companion to active interlocutor. When activated by the user, visual projection is suspended, and the robot delivers explicit reflective prompts through conversation (DG3). These prompts encourage summarization, key claim identification, and evaluation of evidence or limitations, while subtle contingent movements (e.g., nodding or reorientation) help sustain interaction and prompt further articulation (DG4).

C. System Implementation

The system is built on a commercial robot platform, the Realman RM65-B [2]. An Arduino Uno R3 SMD board [3], along with an infrared receiver module and a speaker, is integrated into the base of the robot arm, while a projector is mounted on the end-effector. The system is enclosed with a lampshade, giving it the appearance of a desk lamp.

All components are connected to a laptop running TouchDesigner[4], which orchestrates interaction states, content mapping, and audio output. User inputs are provided via an infrared remote. The active interaction state determines multimodal responses, including robot posture, projected content, and audio feedback. Visual content is dynamically rendered onto paper-based documents, while audio is delivered through the onboard speaker. In Critical Mode, user speech and the reading article are passed to a large language model; a structured prompt template constrained the model to generate open-ended, Socratic-style reflective questions, with temperature set conservatively to promote output coherence.

IV. METHODOLOGY

A. Participants Recruitment

Participants were recruited via social media, a local university, and snowball sampling. Eligibility criteria included: (1) age $\geq$ 18; (2) current university enrollment with a need for academic reading in English; (3) sufficient English proficiency (College English Test Band 4 [CET-4] $\geq$ 550, IELTS $\geq$ 6.0, or TOEFL $\geq$ 70); (4) no cognitive, reading, or uncorrected sensory impairments; and (5) no prior participation in similar reading-robot studies. Master's students were prioritizedParticipants were randomly assig, as they regularly engage in academic reading while still developing critical reading strategies.

We recruited 28 participants (14 female, 14 male), aged 20 to 25 years ($M = 22.69$, $SD = 1.51$). The participants included 3 undergraduate students, 20 master's students, and 5 first-year doctoral students. Participants received a compensation of 120 RMB for their participation.

B. Procedure

The study employed a repeated-measures within-subjects design. The primary independent variable was the presence of robotic support. To avoid potential order and learning effects, essay assignment and reading order were counterbalanced using a Latin square scheme, resulting in four counterbalanced groups (X1, X2, Y1, Y2; see Table I). In the X groups, participants read Article A with robot support and Article B without robot support, whereas the Y groups experienced the reverse assignment. Within each group, participants were further divided based on article order: X1/Y1 read A first, and X2/Y2 did vice versa.

Participants were randomly assigned to one of four counterbalanced groups prior to arrival and completed an informed consent process upon arrival. Audio and video recording consent was obtained. Each session lasted approximately 90 minutes. The following describes the procedure for the robot-supported condition, which was mirrored in the non-robot condition.

TABLE I
COUNTERBALANCED ASSIGNMENT OF READING CONDITIONS

Reading Order	A with Robot B without Robot	A without Robot B with Robot
A first	X1	Y1
B first	X2	Y2

According Fig. 2. Participants first completed a 5–10 minute familiarization phase with the LUMOS system. During this phase, they explored the robot's functionalities using a short sample article to ensure basic operational proficiency.

In the robot-supported condition, participants were given 12 minutes to read Article A while having full access to LUMOS's reading mode features. Following the reading phase, participants completed an 8-item reading comprehension test within 5 minutes. During this phase, they were allowed to revisit the article and continue using the robot's reading support features. Participants were then presented with a critical writing prompt related to the article. They were given 5 minutes for idea planning, during which LUMOS's critical mode remained available, followed by 5 minutes to compose a 300-400 word written response of a critical essay. Although the reading materials were in English, participants were allowed to compose their responses in any preferred language so that they could express their reasoning more clearly. This design decision was made because the study focused on evaluating participants' critical thinking rather than their English writing ability. After completing the writing task, participants filled out two questionnaires assessing their reading strategies and emotional experiences.

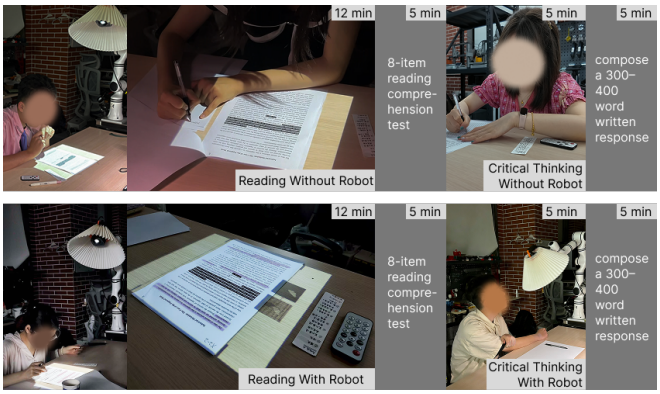


Fig. 2. Study procedure for the reading and critical reflection task (with robot vs. without robot)

Participants were then given a 5-minute break before proceeding to the non-robot condition. In this condition, participants read Article B independently for 12 minutes without the robot, which only provided lighting. They then completed an 8-item comprehension test within 5 minutes, followed by a 5 minute planning phase and a 5 minute writing phase, the same as for Article A. The same questionnaires were administered after completion.

[2]https://www.realman-robotics.com/rm65-6f.html
[3]https://docs.arduino.cc/hardware/uno-rev3-smd/
[4]https://derivative.ca

After both conditions were completed, participants engaged in a 10- to 15 minute semi-structured interview exploring their overall experience, perceived support for critical thinking, and perceptions of the robot.

C. Data Collection and Measurement

First, performance data included reading comprehension accuracy and critical writing responses. Reading comprehension accuracy was calculated as the number of correct answers on an 8-item test adapted from TOEFL reading comprehension formats, with both tests calibrated to equivalent difficulty levels to ensure comparability across conditions. Critical writing responses were used to assess critical thinking and were evaluated using the AAC&U Critical Thinking VALUE Rubric [24], which assesses five dimensions including *explanation of issues*, *use of evidence*, *consideration of assumptions and context*, *articulation of a position*, and *conclusions and implications*. Each dimension is scored on a 4-point scale. Three trained researchers independently rated all responses, and scores were averaged across raters and dimensions to obtain an overall critical thinking score, mitigating individual bias.

In addition, each response was annotated for the number of viewpoints as an indicator of critical thinking depth [25]. Following [25], viewpoints were operationalized as semantically distinct statements by segmenting responses into sentences, encoding them using *paraphrase-multilingual-MiniLM-L12-v2* [26], and applying K-Means clustering with the cluster count determined via the elbow method.

Second, perceived reading and critical thinking strategies were measured using the Metacognitive Awareness of Reading Strategies Inventory (MARSI), a 30-item instrument assessing self-reported strategy use across global (13 items), problem-solving (8 items), and support (9 items) dimensions on a 5-point Likert scale [27].

Third, emotional experiences during reading and writing were measured using the short version of the Achievement Emotions Questionnaire (AEQ-S), a 24-item scale using a 5-point Likert scale [28].

Finally, semi-structured interviews were audio-recorded, transcribed verbatim, and analyzed using open-coding. Two researchers independently coded the transcripts, resolved discrepancies, and iteratively refined themes related to attention regulation, reflective engagement, and perceived support.

V. Result

Results are organized by *RQ1* and *RQ2*. *RQ1* examines comprehension accuracy and MARSI with interview insights on attention and reflection. *RQ2* examines critical writing, AEQ-S, and interview-reported behaviors.

A. Robot support for attention regulation and reflective engagement (RQ1)

We conducted a paired t-test to compare participants' reading comprehension accuracy between the with-robot and without-robot conditions (Shapiro–Wilk, p = 0.141). As shown in Fig. 3 (A), participants achieved **significantly higher accuracy** in the robot-assisted condition (t(27) = 2.61, p = 0.014, Cohen's d = 0.49).

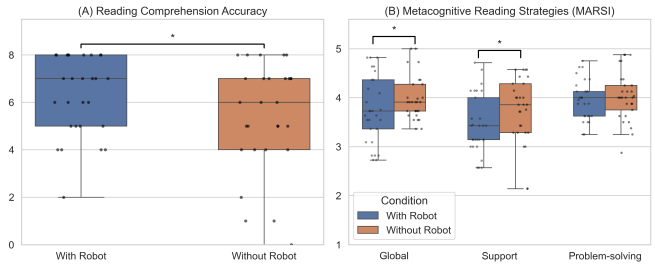


Fig. 3. Effects of robot-assisted reading on attention and reflection. (A) Comprehension accuracy with vs. without the robot. (B) MARSI across global, support, and problem-solving strategies (*$p < .05$).

To further examine reflective engagement, we analyzed MARSI through a paired t-test (Shapiro–Wilk, p>0.05). Results showed **significantly higher** use of **global** (p = 0.0282, d = 0.43) and **problem-solving strategies** (p = 0.021, d = 0.45) when participants interacted with the robot. No significant difference was observed for support reading strategies (p = 0.358). As shown in Fig. 3 (B), this suggests that interaction with the robot is associated with increased use of higher-level metacognitive strategies.

Interview data further illustrate how interaction with the robot supported attention regulation and reflection. X1-1, X1-2, X1-4, X2-6, and Y2-6 described how responding to visual cues and prompts directed their attention toward key parts of the text. For example, X1-4 explained that "*highlighted sentences made me pay closer attention to information I might otherwise overlook during reading.*" And X2-6 reported that "*structural cues such as mind maps helped me understand how ideas were organized across paragraphs and track the overall structure of the article.*"

Importantly, participants emphasized the role of dialogic interaction in supporting reflection. X2-1, X2-6, Y1-3, and Y2-1 explained that engaging with the robot's prompts prompted them to "*reconsider ideas*" and "*explore alternative interpretations of the reading material*". Both X2-1 and Y1-2 noted that discussing ideas with the robot helped them "*clarify understanding*" and "*organize thoughts*" more effectively during both reading and writing tasks.

B. Robot influence on critical reading behaviors and subjective experience (RQ2)

Analysis showed no significant difference in the viewpoints across conditions (Shapiro–Wilk, p<0.05, Wilcoxon signed-rank test, p = 0.67). However, as shown in Fig. 4 (A), the critical thinking scores were **significantly higher** when participants interacted with the robot (t(27) = 3.73, p = 0.0009, d = 0.70), indicating improved quality of reasoning without an increase in the number of viewpoints.

As shown in Fig. 4 (B), results of AEQ-S indicated **significant increases in several positive emotions** in the with-robot condition, including **enjoyment** (p = 0.029, d = 0.436), **hope** (p = 0.007, d = 0.551), and **pride** (p = 0.043, d = 0.401). No significant differences were observed for negative emotions. These findings suggest that interacting

with the robot may enhance participants' positive emotional experience during academic reading tasks.

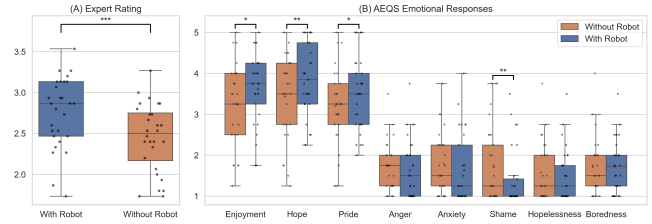


Fig. 4. Effects of robot-assisted reading on critical writing and achievement emotions. (A) Expert ratings of critical writing (robot vs. no robot). (B) AEQ-S after reading. Boxes show interquartile ranges with medians; dots indicate participants ($*p < .05$, $**p < .01$, $***p < .001$).

Interview findings further reveal how interaction shaped participants' critical reading behaviors. Many participants described the robot primarily as a cognitive support tool rather than a social companion. For instance, Y1-3 viewed the robot mainly as "*a tool that helps with reading and thinking about the text.*" Similarly, X2-4 explained that "*articulating my thoughts during the dialog helped clarify my reasoning and refine my interpretations of the article.*"

Furthermore, interview responses suggest that participants were able to benefit from interaction with the robot even when it was not strongly perceived as a social agent. For example, X1-7 noted that "*I can sense that it is listening to me, which helps me stay focused, but I do not really perceive it as having social attributes.*"

VI. Discussion and Limitation

A. Robots as Interactional Scaffolds

Our findings imply a shift in how interactional scaffolding is realized in robot-supported reading. While the content of prompts is generated by a language model, the observed effects are not solely attributable to content generation. Instead, they arise from how prompts are situated within an embodied, reciprocal interaction framework. Rather than attributing improvements in reasoning structure to the robot alone, our findings suggest that structured, reciprocal interaction plays a central role. The robot serves as an embodied mediator that situates LLM-generated prompts within a turn-based, socially grounded interaction, which in turn shapes how users organize and articulate their reasoning. We further observe that this shift is reflected in how reasoning is structured during reading. Rather than expanding the range of ideas, the robot shapes the structure of reasoning. Participants did not produce more viewpoints, but their arguments became more coherent and better organized. This indicates that the robot influences how readers construct and articulate their reasoning, rather than expanding what they think about.

This effect can be understood as a form of interactional scaffolding mechanism that facilitates metacognitive regulation during reading [29]. Visual cues guide attention to key information, as X2-3 noted, "*it points me to the important parts so I know where to focus*." Conversational prompts further encouraged readers to reconsider interpretations and articulate their reasoning, enabling dialogic reflection [30], [31]. Additionally, interacting with the robot enabled the externalization of thinking, allowing participants to verbalize and structure emerging ideas during the reading process [19].

These findings extend prior theories of cognitive apprenticeship [19] and dialogic learning [31]. While these frameworks emphasize making internal reasoning visible through guided interaction, our results imply that such interaction can also structure the organization of reasoning itself. The robot acts not as an information provider, but as an interactional scaffold that shapes how reasoning unfolds.

Importantly, this effect does not rely on strong perceptions of the robot as a social agent. Participants often treated the robot as a functional cognitive tool rather than a socially expressive companion, yet still showed improved focus and reasoning organization. This suggests that in task-specific, short-term contexts oriented toward cognitive support, effectiveness can emerge from how interaction is structured within a reciprocal, embodied framework, rather than from perceived sociality alone. This stands in contrast to relational robot applications, such as those designed for long-term engagement or for users with specific cognitive characteristics [7], where social presence plays a more central role.

B. Emotional and Cognitive Dynamics

Participants in the robot-assisted condition reported significantly higher levels of positive emotions and lower levels of negative emotions. This indicates that the presence of a robotic reading assistant may shape the affective climate of academic reading. Rather than directly improving critical thinking, the robot may facilitate engagement by fostering a more positive emotional experience during reading. This aligns with prior work linking affective states to cognitive engagement, but also highlights the role of embodied interaction in shaping how readers approach challenging texts [32].

At the same time, interview responses indicate a potential trade-off in cognitive agency. While many participants appreciated the prompts and guidance provided by the robot, some noted that repetitive or unclear prompts occasionally disrupted their flow of thinking. This suggests that while robotic scaffolding can support engagement, it may also shift part of the cognitive responsibility from the reader to the system [33]. Designing such systems thus requires carefully balancing guidance with users' autonomy in reasoning [34].

These findings point to key design considerations for future systems. Rather than over-structuring the thinking process, robotic reading assistants should facilitate reflection while maintaining users' sense of control, for example through open-ended or Socratic prompting.

C. Limitation and Future Work

Despite efforts to recruit a diverse sample, participants were primarily drawn from a Chinese cultural context, which may limit generalizability, as cultural attitudes toward technology-mediated guidance may shape engagement with robot-assisted learning. Additionally, participants may have had higher interest in technology, potentially increasing

receptiveness to robotic assistance. While MARSI and AEQ-S rely on self-report, we complemented them with behavioral and performance measures including comprehension accuracy and rubric-based critical writing evaluations. Finally, this study captures only short-term interactions, leaving open whether supported metacognitive strategies would persist with sustained use or whether repeated reliance on robotic scaffolding might reduce autonomous critical thinking over time. Future work should therefore explore fading scaffold designs and the long-term effects of sustained or instruction-integrated use on independent reading strategy development.

VII. CONCLUSIONS

This work explored how an embodied robotic companion supports critical reading and thinking during academic reading. Our findings show that robot-assisted reading improved comprehension accuracy and the quality of critical writing, while increasing the use of global and problem-solving reading strategies and enhancing positive emotional experiences. This highlights the potential of robotic companions to act as interactional scaffolds for academic reading. Notably, in this task-specific, short-term context, these benefits emerged without strong social presence, suggesting that subtle, non-intrusive interaction may serve as an effective paradigm for cognitively demanding tasks.

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